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Hotspots and sunspots: surface tracers of deep mantle convection in the Earth and Sun

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ABSTRACT

The pattern of new appearances of hotspots on the Earth is investigated using available age data. The worldwide total of Cenozoic and Mesozoic hotspots, predicted by extrapolation from the observed number of continental flood basalts, is ~ 40, in agreement with Crough's counts. There are found to be no true antipodal pairs. In one interpretation of the data, new appearances of hotspots occur first at high latitudes in both hemispheres and then migrate toward the equator; shortly before the migration cycle is finished, the next cycle begins. A relative deficiency of hotspots, however, is observed in very low equatorial and very high polar regions. In addition, hotspots occupy two large hemispherical groups in longitude that slowly drift in the same direction as the axial body rotation. An observed magnetic superchron seems to end when a new hotspot migration cycle in latitude begins; but consecutive superchrons show opposite polarity.

Although the hotspot data are rather sparse, their suggested patterns resemble the well-known patterns of complexes of active regions on the Sun, as exemplified by proxy data, such as sunspots. Both the Earth and the Sun possess large convecting, rotating and magnetized mantles, in which the characteristic surface tracers are believed to reflect the patterns of convective phenomena very deep in the mantle (even though the tracers themselves—hotspots and sunspots—are certainly not analogs of each other). The present study supports existing theoretical ideas that the large-scale patterns of deep mantle convection in the Earth and Sun may fundamentally resemble each other, despite the enormous difference in their molecular viscosities. Magnetic polarity reversal histories also show close similarities in the two bodies, suggesting the operation of basically similar convective dynamos. However, the Sun has displayed no known analog of the Earth's magnetically disturbed intervals.

1. Introduction

The existence of stationary hotspots in the Earth's upper mantle has been inferred from observed chains of volcanoes that lie far from subduction zones and are older in the direction of lithospheric plate movement [1]. Many other hotspots have been identified by noticing topographic swells that cover a large area. The total number of hotspots is uncertain: Morgan [2] originally listed 19, which was increased to 24 by Chase [3], to 66 by Wilson [4], and finally to 117 by Burke and Wilson [5] and Vogt [6]. A more conservative and realistic estimate of 42 has recently been made by Crough and Jurdy [7] and Crough [8]. The majority of hotspots are correlated with highs of the residual geoid that is obtained after elimination of the presence of subducted lithospheric slabs [3,7]. These highs cover about half the Earth's surface within two huge ellipses, one running east–west in the Pacific Ocean and the other trending roughly north–south between the North Atlantic Ocean and the Indian Ocean. Statistical analyses suggest that hotspots concentrate to some extent toward the mid-ocean ridges [2,9,10] but that they contain no strong higher angular symmetries [11,12], although weak ones may exist [12,13].

These global characteristics point to a deep source for the hotspots: probably at least as far down as the 670 km level (where a marked seismic discontinuity occurs) or, more probably, the level of the core–mantle interface itself, 2900 km below the surface (about half of the Earth's radius). Regardless of the depth of their origin, hotspots are almost certainly associated with mantle convection and have usually been explained as either rising plume heads [14,15] or primary upwelling features of the general circulation itself [16–18]. Since thermal convection in the Earth's mantle is extremely slow, owing to the very high viscosity of the semifluid rocks, hotspots can be expected to be roughly fixed in location with respect to each other for hundreds of millions of years [19].

As possible probes of mantle convection, and as useful reference points on the globe for reconstructing past continental positions and establishing true polar wander paths, hotspots possess an obvious geophysical importance. No previous study, however, seems to have been made of the evolution of the hotspot distribution in time and space. This is presented here with the limited material available. The inferred patterns of convective phenomena very deep in the mantle turn out to be rather complex.

Since little is known for certain about the real nature of these patterns, analogies with other large astrophysical convecting systems can and should be usefully sought. Here, a possible analogy with the Sun's mantle is pointed out and explored.

2. Hotspot ages, locations and numbers

If one is to make an effective empirical study of long-term changes in the Earth's mantle, a reliable chronology of new appearances of hotspots at the Earth's surface is required. High accuracy of the ages is not needed, however, because the mantle turnover time is measured in hundreds of millions of years. Here, the age of a hotspot is defined as the initiation of hotspot activity at the surface as marked by massive flood basalt eruptions [2]. Ages and geographical coordinates of thirteen hotspots, all post-Paleozoic, are listed in Table 1 [15,19–23]. (Lower limits to the ages of a few other hotspots are known from dated volcanic traces, but these are not useful for the present purpose; additional Pacific Ocean hotspots [24] could be included if their ages were known more precisely.) In some cases, where there are two, neighboring hotspots, the wrong hotspot may have been assigned to a known flood basalt province. No important error will be incurred in the present analysis, however, because highly precise coordinates of the hotspots are not required. Notice that most of the known flood basalt provinces lie on continents, owing to the ease of their discovery there. A simple extrapolation from the observed number of continental flood basalts suggests that a total of ~ 40 continental and oceanic flood basalts worldwide have

TABLE 1

Dated hotspots and associated flood basalts

Hot spot	Longitude	Latitude	Age (Myr)	Flood basalt	References
Yellowstone	−111	43	17	Columbia River	[19,20]
Afar	43	10	35	Ethiopian	[19,20]
Iceland	−20	65	62	Brito-Arctic	[15,20]
Réunion	55	−20	66	Deccan	[15,20]
Marion	38	−47	90	Madagascar	[15,21]
Galápagos	−92	0	90?	Caribbean?	[22]
Kerguelen	69	−49	115	Rajmahal/Kerguelen	[15,22]
Louisville	−139	−50	121	Ontong-Java	[22,23]
Tristan da Cunha	−13	−36	135	Serra Geral/Namibian	[15,20]
Bouvet	2	−54	180	Antarctic/South African	[15,20]
Great Meteor	−28	30	200	Eastern North American	[15,20]
Azores	−28	39	200	Eastern North American	[15,20]
Jan Mayen	−8	71	250?	Siberian?	[19,20]

erupted during the past 250 Myr. It may be not merely coincidental that the total number of geologic stages (marked by marine extinctions) was 48 during the same time period.

Ten of the thirteen hotspots listed in Table 1 are found in Crough's [8] critical compilation of 42 hotspots over the globe. Although the Marion, Louisville and Jan Mayen hotspots do not appear in Crough's compilation, his study is nevertheless assumed to be more or less statistically sound, because it lists only one volcanic center per topographic swell and it omits all the volcanic centers near trenches that may be related to subduction. As a homogeneous and representative sample, which is possibly very nearly complete in view of the continental flood basalt statistics, the slightly augmented set of 45 hotspots is adopted here. Roughly a quarter of them lie under continents, as might be expected for a random sample of points distributed over the globe. This statistical feature, despite the well-known asymmetry of the hotspot distribution, at least lends credence to the idea that there is no significant bias toward suboceanic hotspots, which are much easier to detect.

3. Hotspot distribution in time and space

The latitudes of the 45 adopted hotspots show a very peculiar distribution, being mostly concentrated in two parallel belts on either side of the equator (Fig. 1). These belts stretch approximately from 10° to 50°, with relatively few hotspots appearing at either equatorial or polar latitudes.

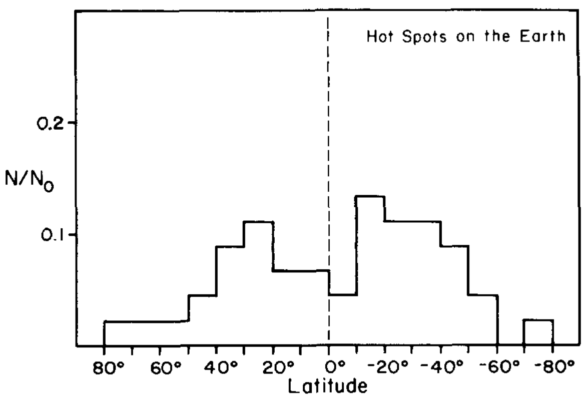

Fig. 1. Present distribution of hotspots on the Earth by geographic latitude ($N_0 = 45$).

TABLE 2

Frequency of hotspots in equal-area bands of latitude

Latitude range (°)	Number (Morgan)	Number (Crough plus)
0–10	2	5
10–20	3	9
20–30	4	12
30–42	4	7
42–56	3	9
56–90	3	3

The peak concentration falls around 25°. Although the 117 volcanic centers claimed as hotspots by Burke and Wilson [5] scatter much more widely, their list of hotspots probably contains many non-independent sources. The original set of nineteen hotspots identified by Morgan [2] closely follows the distribution in Fig. 1.

Statistically, it is more meaningful to derive the frequencies for bands of equal area than for bands of equal latitude range. Such a tabulation is presented in Table 2, where northern and southern latitudes have been combined in order to reveal the statistics better. Owing to the combination of a non-extreme (though peculiar) frequency variation and small numbers, a chi-square test is unable to determine at the 2σ level whether the frequency variation is random or non-random. One strong indication that it is physically real comes from the fact that when Morgan's [2] original sample of nineteen hotspots was increased to the present 45, the relative frequency distribution remained essentially unchanged, as shown by Table 2. Another indication will emerge from the solar analogy discussed below.

Although the Earth's hotspots are, individually, almost fixed in the upper mantle, they show a possible latitudinal pattern of new appearances that migrates slowly with time (Fig. 2). In this view, at the beginning of a migration cycle, hotspots form at middle to high latitudes. The location of new hotspot formations then drifts toward low to middle latitudes. Hotspots are most active at a phase [24] that is identified here as being mid-cycle. Later, a new cycle begins. There may be a slight overlap between consecutive cycles. Figure 2 suggests that the current cycle began between 70 and 90 Myr ago, and that the previous cycle lasted ~ 180 Myr. Although the available data are sparse, and oceanic subduction losses must make it difficult to extend the data back in time, this pattern is also suggested by the solar analogy, as discussed below. A different interpretation, in which hotspots form for a long time predominantly first in one hemisphere and then in the other, seems to be less likely.

In longitude, hotspots on the Earth tend to populate, approximately equally, two broad zones whose centers are separated by 120°: a western (Pacific area) zone and an eastern (Africa area) zone. Incorporating the present age data, Fig. 3 suggests that the whole pattern of new formations of hotspots drifts slowly eastward (that is, in the direction of the Earth's rotation). A least-squares regression line fitted to the eastern hotspot data indicates an average propagation rate of 0.31° ± 0.14° (1σ) per million years. The slope of the line is thus non-zero at the 2σ level. Since the same slope fits the sparser western data very well, this slow drift appears to be confirmed, although additional hotspot ages would be useful. One full circuit requires about 1200 Myr, but the uncertainty is at least several hundred million years. In any case, Fig. 3 indicates that the drift in longitude is much slower than the drift in latitude.

It is not easy to interpret these complex observations. A possible explanation is that, as the slow movement of the convecting masses within the mantle leads to a change in the moments of inertia of the Earth, the mantle, as a whole, may shift with respect to the axis of rotation [25]. Observationally, true polar wander during the past 200 Myr might have attained as much as 25° [26], but this alone is not enough to explain the large latitudinal succession of new hotspot appearances. The eastward drift of new appearances, however, could be related to the westward rotation of the lithosphere with respect to the present day hotspot reference frame (which is assumed to be immobile); this rotation amounts to some 0.11–0.33°/Myr, as estimated from present day plate kinematical data and, independently, from Cenozoic geological data [27–29]. Alternatively, there could be a toroidal drift of the overall pattern of mantle convection, which may be related to the general convective turnover itself. The turnover time has been estimated from the ages of recycled mid-ocean ridge basalts to be about 1800 Myr [30]. The present results are clearly not conclusive about whether hotspots do or do not constitute an adequately stationary reference frame for geodynamical studies covering time spans of hundreds of millions of years.

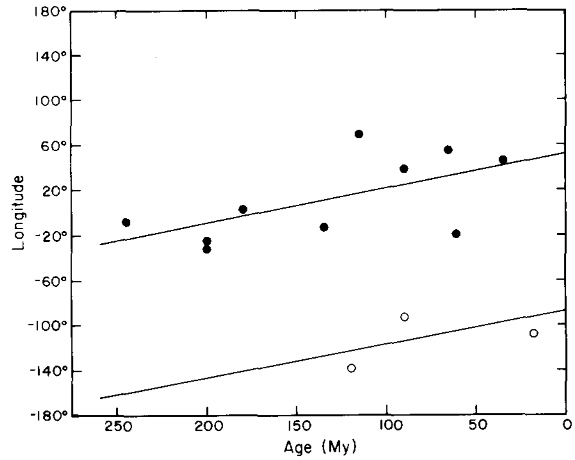

Fig. 3. New appearances of hotspots since the Paleozoic as a function of geographic longitude. A regression line is fitted only through the eastern hotspots, but a parallel line is run through the western hotspots.

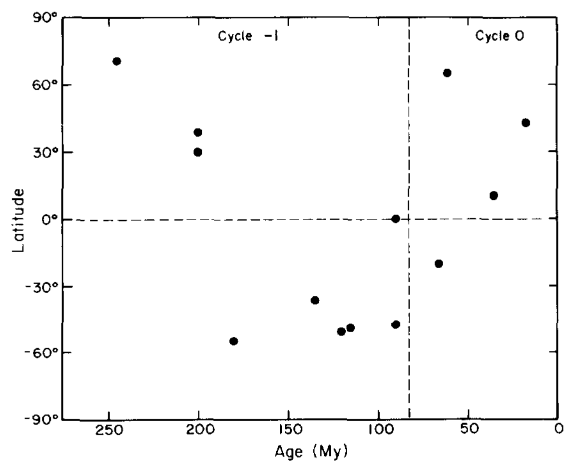

Fig. 2. New appearances of hotspots since the Paleozoic as a function of geographic latitude. Parts of two possible geologic cycles are identified. Alternative interpretations of the data, however, can be made.

4. Antipodal pairs of hotspots?

Due to the arrangement of the two hotspot longitude zones on opposite hemispheres of the Earth, as well as the likely near simultaneous appearance of new hotspots in two latitude belts equally above and below the equator, about half of new hotspots are expected to erupt in large areas that are roughly antipodal to each other. In contrast to this low-frequency partitioning of new hotspot appearances over the globe, Rampino and Caldeira [31] have proposed that the observed hotspot distribution contains a statistically significant number of individual *pairs* that are nearly antipodal to each other. Such pairing, if real, would have interesting implications, and can be critically tested with the age data in this paper, because antipodal pairs of hotspots are expected to be nearly coeval for any physically plausible mechanism of formation [31]. Why all hotspots are not antipodally paired, however, would remain a problem. The sample of 42 hotspots from Crough and Jurdy [7] that Rampino and Caldeira adopted is essentially the same as the 45 hotspots adopted here, of which 29% have been dated (Table 1). Four, nearly coeval, pairs occur in the table, falling at or close to ages of 64, 90, 118 and 190 Myr. However, the longitude differences between the members of these pairs are respectively 75°, 130°, 208° and 30°: all very far from the predicted 180°. Members of one of Rampino and Caldeira's antipodal pairs, Yellowstone and Kerguelen, have been dated, but their ages are 17 Myr and 115 Myr, respectively. It seems safe to conclude that the six antipodal pairs that Rampino and Caldeira noted are merely statistical flukes of geography. In fact, of the two null hypotheses that they adopted for numerical tests of statistical significance, one is the uniform distribution. Use of such a hypothesis practically guarantees rejection, because the hotspot distribution is already known to be geographically bimodal, to lowest order. The other hypothesis they adopted is a randomized distribution of hotspot positions, in which the hotspots are moderately displaced from their actual positions. This assumption can test robustness, but not statistical significance, because the null hypothesis here is merely the observed distribution itself, slightly perturbed!

5. Solar mantle phenomena

Like the Earth, the Sun's mantle convects as a result of heating from below [32]. The Sun's mantle, however, consists almost entirely of an inviscid hydrogen and helium plasma, extending about 2×10^5 km below the surface (about 30% of the solar radius). Rotation of the mantle as a whole is only approximately rigid [33,34], the mean period at the surface being 25 d near the equator and 30 d near the poles. A hypothetical giant convection cell in the mantle might turn over in a similar, but independent, period of about 2 months [35]. However, the most recent numerical simulations and laboratory experiments suggest that large-scale mantle convection in the Sun, even though it is relatively rapid and turbulent, probably occurs not in cells but rather in sheet-like or plume-like features [32,36,37]. Many of its predicted properties in the deep interior are like those in much more rigid bodies, including descending slabs and ascendant plumes rising from the core–mantle interface. In this respect, the Sun's largest convecting elements resemble those seen in numerical and laboratory simulations of terrestrial mantle convection [15–18]. Indeed, the similarity has been implicitly commented on [32].

Observed magnetic activity at the Sun's surface displays a well-known cyclicity, whose irregular time intervals range from 7 to 17 yr but whose average period is 11 yr (22 yr for a full polarity cycle). This activity produces, among other phenomena, the cool and magnetically intense sunspots, which last only a few days. The Sun's general magnetic field, however, is believed to be generated by dynamo action very deep in the convective mantle and much of it (including all of the observed toroidal component) is then slowly buoyed to the surface in magnetic flux loops. Accordingly, observed major active regions are believed to be surface tracers of the large-scale patterns of deep mantle convection [32]. The long-term behavior of major active regions may consequently be compared with that of the Earth's hotspots. Although sunspots are minor magnetic phenomena and cannot possibly be construed as analogs of terrestrial hotspots, they, nevertheless, essentially reflect the behavior of the large active regions and can be used as surrogates for them.

Solar activity indicators display an arrangement in latitude that is analogous to that of terrestrial hotspots. The distribution of sunspot groups during solar cycle 21, specifically for the years 1977–1987 [38], is exhibited in Fig. 4. Most

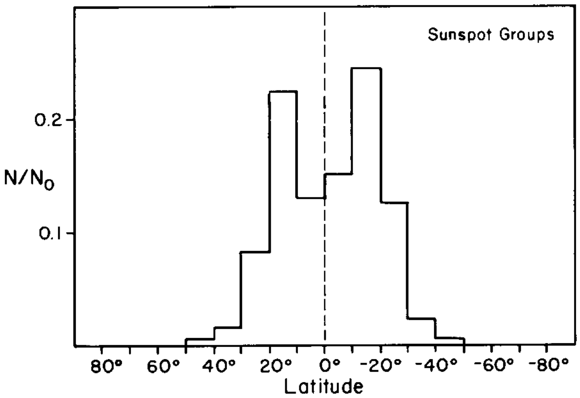

Fig. 4. Time-integrated distribution of sunspot groups for the years 1977–1987 in heliographic latitude ($N_0 \approx 2300$).

of the spot groups occupy latitudes 10–30°, with a peak occurring around 15°. Solar active regions are thus somewhat less widely dispersed toward the poles compared to hotspots on the Earth.

The solar analogy to Fig. 2 is the famous Maunder "butterfly" diagram, which has been reproduced many times (for example, [39]). The total spread in latitude exhibited by sunspot groups, especially around the time of mid-cycle when sunspots are most abundant, is very wide (a spread of up to 30° in each hemisphere). Consecutive cycles partially overlap. The equatorward migration time for new appearances of sunspot groups is the same as the general period of magnetic activity indicators: about 11 yr. As in the case of hotspots on the Earth, the migration time is orders of magnitude longer than the period of rotation.

Preferred longitude zones also occur on the Sun [38,40–42], although their existence is still slightly controversial. Broadly considered, the active longitudes containing most of the sunspots may be grouped into two wider zones centered about 180° apart. These zones appear to drift slowly around the Sun (in the frame of heliographic coordinates) with a period that is between a fraction of one and several sunspot cycles long. The measured drift is westward (that is, in the direction of the Sun's rotation). The obvious requirement that the active zones be rigidly rotating in order to persist so long indicates a very deep source for the disturbance.

6. Discussion

6.1. Terrestrial and solar mantle convection

The formal congruences between the global patterns of solar active regions and geologic hotspots may reflect a true similarity between convective phenomena occurring very deep within the mantles of the Sun and Earth. If so, differential rotation (absent in the Earth) and precession (effectively absent in the Sun) are unlikely to play a role in setting up these patterns. The solar analogy can be advanced to infer that a system of whole-mantle convection in the Earth would probably prevail over a two-tiered system of mantle convection (although both systems may actually operate in both bodies [30,32]). The analogy cannot be pushed too far, however, because the molecular viscosities in the two bodies are vastly different, and continents and tectonic plates on the Earth probably exert some control over hotspot positions [3,7,11,43,44]. A uniquely terrestrial surface boundary condition of this sort may well explain some of the observed "excess" in the dispersions of the latitudes and longitudes of hotspots.

6.2. Terrestrial and solar convective dynamos

Magnetically, the Sun and Earth share some important similarities [45]. Both bodies probably generate their magnetic fields by convective dynamo action not far from the core–mantle interface: in the lower mantle for the gaseous Sun and in the liquid outer core for the semisolid Earth. The surface magnetic field strength of the equivalent centered axial dipole is ~1 gauss at the poles of both bodies. Both bodies exhibit at their surfaces the easily observable poloidal part of the field, but in the Earth the toroidal part is hidden from view by the nearly solid mantle.

The Sun's pseudo-dipole field reverses once every ~11 yr. Near the poles, the reversal takes place a few years after the beginning of a sunspot migration cycle in latitude [46]. However, it is not yet clear what fraction of the observed polar field belongs to a true dipole field, since bipolar spot groups at high latitudes start to display a reversed polarity arrangement exactly at the beginning of a new migration cycle [39].

Although the Earth's dipole field undergoes relatively much more frequent reversals (once every few hundred thousand years) during most of the course of a hotspot migration cycle, its polarity has remained constant for long periods, most recently during the Cretaceous normal superchron (118–83 Myr ago) and the Permo–Carboniferous reversed superchron (320–250 Myr ago). Each time that the polarity reversals have recommenced, following a long quiet interval, has marked the apparent beginning of a new hotspot migration cycle in latitude (Fig. 2). Despite the great frequency of reversals during the disturbed periods, it is interesting that the polarity of the undisturbed intervals has switched from reversed to normal between the two most recent intervals, just as if the quiet interval were the remembered, true state. The fact that the maximum magnetic field strength was apparently identical during the most recent quiet and disturbed intervals [47] indirectly supports the hypothesis of a remembered state. Further back in time, this pattern persists, although the data become much less reliable (there was probably a Silurian–Ordovician normal superchron and a Cambrian reversed superchron [48]).

It may be tentatively concluded that, whatever mechanism it is in the Earth and Sun that abruptly changes the polarity (and also turns up the Earth's reversal frequency), it seems to be closely linked to the mechanism that produces the new spot cycles in both bodies. If this linkage occurs at or near the core–mantle interface (as seems likely), it follows that, since the highly fluid nature of the region containing the convective dynamo must be dynamically adjusted to the body's axial rotation, such an adjustment will impart a preferred directionality with respect to the axis of rotation to any triggered convective disturbance. As soon as this disturbance reaches the surface, a region of potential hotspot activity will develop. The total time lag may be months for the Sun and a few tens of millions of years for the Earth.

7. Conclusions

The complex pattern of new hotspot appearances at the Earth's surface has been examined in this paper. The relatively complete statistics of continental flood basalt eruptions suggests the formation of a total of ~ 40 hotspots worldwide during the Cenozoic and Mesozoic, in close agreement with Crough's counts. No true antipodal pairs are found. Hotspots tend to concentrate mainly in mid-latitudes, but the pattern of new appearances of hotspots may migrate from high to low latitudes in both hemispheres in long cycles, and may also drift much more slowly prograde in longitude. The beginning of a new latitudinal migration cycle marks the end of a long magnetic superchron, whose fixed polarity is opposite from that of the next superchron. In support of this picture, which is still tentative, the Sun's convective mantle seems to provide a plausible analogy, although sunspots and large solar active regions (the surface tracers of what is convectively occurring very deep in the mantle) are not, themselves, analogs of hotspots.

An empirical working model for deep-seated convective phenomena in the Earth's mantle has been outlined. In this phenomenological model, hotspot observations can be fitted and interpreted with some credibility. So far, the model looks promising and makes some clear predictions for future verification, specifically the temporal and spatial patterns of hotspots in the largely unexplored pre-Mesozoic. Additional ages for Mesozoic and Cenozoic hotspots, however, are desirable in order to confirm or refute the validity of the model.

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